

NASA's Virtual Product Laboratory: An Overview

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ABSTRACT

The Virtual Product Laboratory (VPL) developed by NASA's Commercial Remote Sensing Program at the John C. Stennis Space Center is a tool that enables simulation, design, and verification of remote sensing systems within a software (virtual) environment. The VPL can serve industry, government, and university communities by providing a means to conduct system trade studies, optimization, visual modeling, and data product simulations entirely in a virtual environment. The VPL can serve as a complete end-to-end simulation tool capable of producing system and subsystem performance characterizations, system optimization, and simulated data products or as a means of evaluating any one component of a remote sensing system.

In this paper, we present an overview of the VPL capabilities. The VPL functional areas include Requirements, Design & Analysis, Simulation, Project Management, Knowledge Base, and Help. A description of each function along with the tools and techniques used to accomplish these functions will be provided. When possible, sample VPL displays and products will be used in the presentation.

Key Words: Virtual, Simulation, Knowledge Base, Trades, and Modeling.

1. INTRODUCTION

Within the last decade, many organizations within industry and government have developed virtual design/engineering capabilities. The majority of these efforts have been customized to serve a single, specific mission, with significant time and resources devoted to subsystem and component-level detail. The goal of the Commercial Remote Sensing Program's (CRSP) Virtual Product Laboratory (VPL) is to provide a system-level simulation and modeling

environment to support a variety of missions within the U.S. commercial remote sensing industry and NASA's Earth Science Enterprise. The VPL provides access to a set of simulation and modeling tools that can be customized for spacecraft system performance characterizations, system trades and optimization, data product simulation, and business decision making. The VPL can serve industry, government, and academic communities by providing an end-to-end modeling environment that takes a user from remote sensing requirements development through end product simulation and cost-benefit analysis (see Figure 1). Customization necessary to support specific missions occurs during collaboration with VPL users.

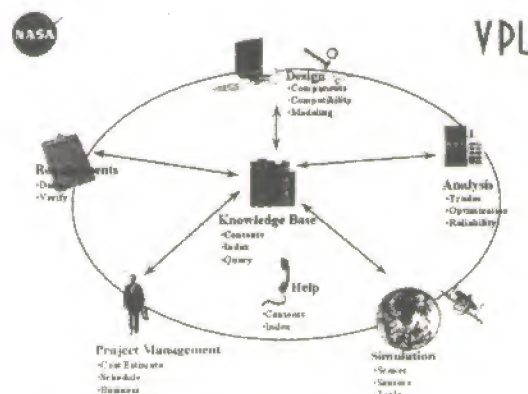


Figure 1. VPL Functional Process Flow

The methodology for developing the VPL consists of rapid prototyping, maximizing the use of Commercial off-the-shelf (COTS) and government off-the-shelf (GOTS) hardware and software, and leveraging of existing capability within industry and government. The VPL development is an evolving process that follows two parallel paths - a standard development

path and a rapid prototyping path. The standard development path comprises the following steps:

1. Requirements Assessment and Selection - The team identifies the requirements and tasks to be implemented during the current development phase.
2. Software/Hardware Evaluation and Design - The team evaluates available COTS and GOTS software to determine if any existing tools will aid in achieving VPL requirements. If no tools are available, the VPL team designs customized software. The team then identifies hardware capabilities required to support the recommended software.
3. Software/Hardware Procurement and Development - Software and hardware purchases are initiated. Any customized software development also occurs during this time.
4. Implementation - New hardware and software tools are incorporated into the existing VPL framework. Training, testing, and demonstration of the new tools occur at this time.
3. Design - For each project, a conceptual design is developed. The design serves as a way of communicating the plan for the demonstration.
4. Development and Initial Test - Prototype development occurs during this step. This may consist of developing a new VPL function or enhancing an existing function. The prototype is then tested against the customer's requirements.
5. Use and Modification - The prototype is used by VPL team members and the customer for an extended period of time. Extended use helps to identify necessary modifications.
6. Integrate within Existing VPL Framework - If deemed beneficial, the demonstration is integrated with all other VPL software via customized interface software development.

The standard development is typically performed in phases, with each phase lasting approximately six months. Essential VPL capabilities, such as basic optical sensor simulation and knowledge base development, have been implemented using this approach.

The rapid prototyping path involves the use of VPL expertise and tools to perform short-term projects and demonstrations that address a specific objective or customer need. The prototypes generate user feedback that serves as input to the VPL development process. Addressing customer-defined problems using the VPL helps the project team gain a better understanding of customer needs. The following steps are performed for each project demonstration:

1. Define Objectives and Schedule - Each project demonstration begins by collaborating with the customer to define objectives, requirements, and schedule. Customer deadlines and milestones typically drive the development schedule.
2. Form Team - A small team is formed to focus on prototype development. Team members are selected based on the specific skills necessary to meet customer objectives.

Steps one through four of the rapid prototyping path typically last between one and two months. Upon completion of step four, the prototype is considered operational. Further refinement and automation performed during steps five and six may require additional time.

The approach used in VPL development involves maximizing the use of COTS and GOTS hardware and software and minimizing the amount of custom software development. Additionally, existing expertise and capabilities are continually sought for all modules of the VPL so that maximum leveraging and technology sharing occur. To date, CRSP has leveraged from space system design expertise within NASA's Langley Research Center (LaRC) for the development of engineering design and modeling functions. Capabilities and tools from industry, government, and academia have also been implemented. When leveraging capability from off-site locations, virtual interfaces and networks are put in place so that seamless connectivity exists among all distributed components.

II. SYSTEM DESIGN

The VPL system includes all hardware and software required to develop, demonstrate, and operate the VPL. The system architecture is implemented using a distributed network of interrelated hardware and software systems. Where possible, hardware and software have been selected that drive the VPL architecture to a simpler, more manageable system.

Hardware

VPL hardware architecture is driven by the software applications and support systems needed to implement the VPL requirements. The hardware consists primarily of Windows NT and UNIX based workstations. The workstations interact via the Stennis Space Center (SSC) CRSP Intranet, a 10-megabits-per-second Ethernet network using Transmission Control Protocol/Internet Protocol (TCP/IP) (see Figure 2). The VPL hardware supports local and distributed activities.

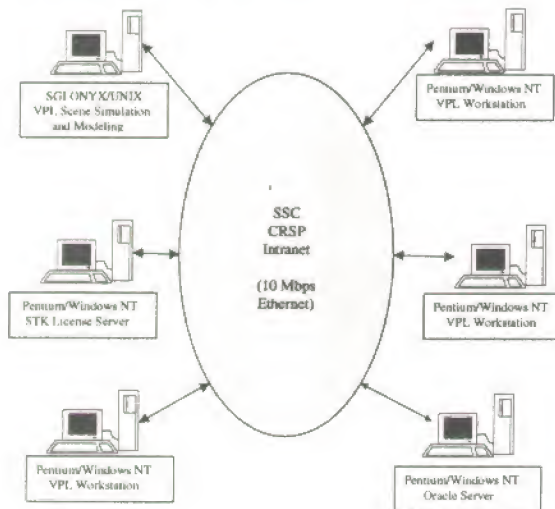


Figure 2. VPL Hardware Architecture

Software

The VPL software architecture maximizes the use of COTS and GOTS software. A graphical user interface (GUI) has been developed to integrate these tools and to provide a consistent look and feel to the software. Software tools are integrated into the GUI using custom software and standard communication protocols, such as Inter Process Communications (IPC) and Remote Method Invocation (see Figures 3 and 4).

The VPL software is currently accessible locally (at SSC) and remotely (from off-site) through the use of terminal server client software for Windows NT. Personal computers running Windows NT or Windows 95 are capable of accessing most VPL functions.

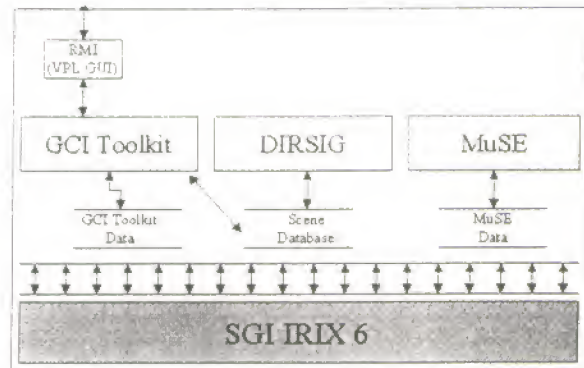


Figure 3. VPL UNIX Software Configuration

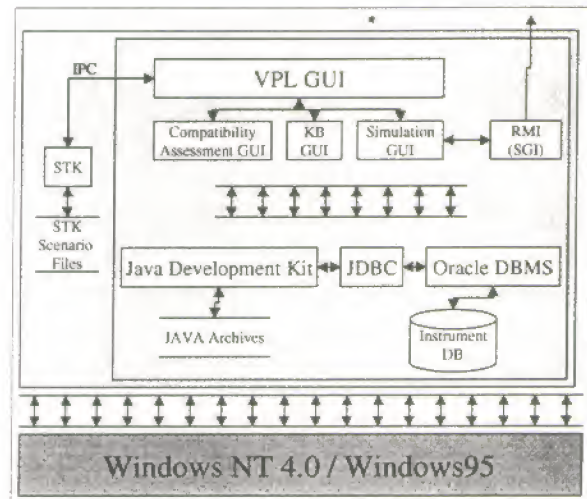


Figure 4. VPL Windows NT Software Configuration

III. VPL FUNCTIONAL AREAS

The following paragraphs provide an overview of the VPL functional areas. Each section describes the planned capabilities for the function along with a description of current functionality and future enhancements.

Knowledge Base

At the core of the VPL system is the VPL Knowledge Base. The Knowledge Base will provide access to remote sensing industry-related information, products, and services. The types of information provided will include remote sensing image data; infrastructure components, such as sensors and platforms; current and planned remote sensing missions; academic and industry research and development; marketing information; technologies within commercial industry, government, and academia; and user-defined information. These data

are provided to the rest of the VPL functions to support user activities.

The VPL Knowledge Base is currently implemented using Oracle Enterprise Edition Software, version 8.1.5, on a Windows NT platform. Oracle provides the traditional relational database management system along with an object oriented database management capability. The Knowledge Base also utilizes several Oracle data cartridges for handling spatial data, imagery, and time series data.

Database tables have been defined for sensors, platforms, launch vehicles, and associated manufacturers/vendors. Currently these tables support only information on optical sensors (specifically panchromatic, multispectral, hyperspectral, and thermal) and related missions. Sensor information includes general data (sensor name, sensor type, manufacturer, etc.) system characteristics; power requirements; stabilization methods; and subsystem data including swath, ground sample distance (GSD), radiometric accuracy, field of view, aperture shape and diameter, scan rates, integration times, and band data (number of bands, band width, spectral band purity, spectral response, calibration information, etc.). The Knowledge Base team is currently populating these tables with optical sensor and mission data. The next task for the team will be to develop and populate the table structures for active sensors (synthetic aperture radar (SAR), light detection and ranging (LIDAR), etc.).

A graphical user interface has been developed in Java to allow users to add, view, modify, and delete data records. The GUI software interfaces to the Oracle database using Oracle's Java Database Connectivity (JDBC) driver. Figure 5 represents a sample data entry screen. User and group access privileges will be implemented to protect trade secrets and proprietary information for private developers.

The Knowledge Base will also provide users with the capability to execute simple and complex queries. Example queries include searches for instruments to meet user-defined requirements or queries on industry technology offerings. The user can specify the format for the query results, review the results, generate hard copy reports, and save the results for use with other software tools.

Figure 5. Sample VPL Data Entry Screen

Simple, ad hoc user queries have been implemented using the Oracle Discoverer tool. Standard templates (workbooks) for basic user queries have been developed. Users can customize these queries by specifying their own unique search criteria. Advanced users have the ability to create and save their own queries. Figure 6 depicts a typical Discoverer display screen.

Sensor	Manufacturer	Country	Year Manufactured	Sensor Type	Operator
1. AC	Unknown	US	1999	Panchromatic	Navy
2. AL	Unknown	US	1999	Multispectral	DOE
3. AL	Unknown	US	1999	Panchromatic	DOE
4. ASTER	Jet Propulsion Laboratory	US	1997	Multispectral	NASA
5. HSI	TRW	US	1997	Hyperspectral	DOE
6. MRSI	Jet Propulsion Laboratory	US	1997	Multispectral	COM
7. MTI	TRW	US	1997	Multispectral	NASA
8. NEMO	SPACE TECH DEV	US	2000	Hyperspectral	Army
9. NEMO	SPACE TECH DEV	US	2000	Panchromatic	Army
10. QuickBird-1	Eastman Kodak Commercial and G-	US	1999	Multispectral	COM

Figure 6. Oracle Discoverer Display Screen

As the VPL matures, users will require the capability to perform sophisticated queries on diverse data sets. To meet these challenges, the Knowledge Base will need to evolve from a relational database system to an expert system. The expert system will provide a rule base capability, derived from expert and historical data, to perform specialized problem solving. The Knowledge Base will be capable of storing data, relationships between data, fuzziness, and heuristics. The system will provide the capability to test hypotheses, make estimates, and solve problems based on data and models contained in the system. Additional tools will be added to support natural language queries.

Simulation

The simulation function allows users to generate simulated remote sensing data products. VPL tools will enable the simulation of various types of data (reflective multispectral, hyperspectral, SAR, LIDAR, thermal, science measurements, etc.) as derived from instrument characteristics. Resulting simulated products will include the effects of any and all system errors, such as those incurred by spacecraft jitter, out-gassing, or atmospheric effects. CRSP's expertise in the areas of data simulation, image rendering, and multidimensional visualization will provide advanced data analysis and image product generation capabilities.

Users will have the capability to simulate remote sensing system data and imagery. Simulated data sets will be based on instrument characteristics, observational parameters, existing data, and ground truth data. These products can be used to assess instrument design, performance, and error budgets. Data simulations will involve two steps: scene generation and sensor simulation. The system will provide the capability to perform high fidelity scene simulations using ground measurements (ground truth databases) and actively maintained target models. Scenes will be generated using atmospheric radiative transfer models. Major factors in scene simulation will include solar and view geometry, date, time, climate, weather, aerosol type, ground material spectral reflectance, material mix, digital elevation model, and radiosonde data.

The VPL will provide the capability to simulate performance for the following types of sensors: high spatial resolution, multispectral, hyperspectral, thermal, LIDAR, and SAR. Sensor simulations (models) will include various types of sensor modulation transfer functions (MTF's), such as detector, motion, jitter, optics, and atmospheric turbulence, as well as sensor spectral response and noise characteristics. The user will have the capability to modify MTF parameters to analyze their effects on resultant data products.

The current simulation capabilities are focused on physics-based simulations of optical sensors. The simulations involve two steps: scene generation (Cao et al., 1999) and sensor simulation (Blonski et al., 1999). Synthetic scenes are generated using material databases, spectral reflectance, and mixing of materials. For reflective simulations, a scene is simulated based on the solar irradiance at the time of image acquisition, the reflectance of the ground material, and atmospheric absorption, scattering, and

aerosol characteristics. In thermal infrared simulations, the surface temperature and emissivity of the objects on the ground, as well as the path radiance, are used in predicting the at-sensor radiance. In-band at-sensor radiance values are computed by convolving the spectral response of the sensor with the at-sensor spectral radiance curve.

The VPL utilizes several synthetic scene generation software packages, including Global Change Initiative (GCI) Tool Kit from Photon Research Associates, Digital Imaging and Remote Sensing Image Generation (DIRSIG) from the Rochester Institute of Technology, and custom software developed to simulate simple target scenes. GCI Tool Kit uses rasterized models of terrain and clouds and atmospheric modeling based on MOSART. DIRSIG uses high-resolution, facetized models of terrain and 3-dimensional objects and atmospheric modeling based on MODTRAN (Schott et al., 1999). The custom software uses high-resolution 2D models (edge targets, radial targets, roads, bridges, etc.) and atmospheric modeling based on MODTRAN (Berk et al., 1998). Figure 7 represents a simulated scene of the SSC Verification and Validation target.



Figure 7. Simulated Verification and Validation Target at SSC. Actual site (left) includes 80m x 80m x 70m 8:1 contrast ratio edge targets, 35m x 40m 4-step gray scale targets, and a 130m radial target. Synthetic scene (middle) generated by custom software and MODTRAN has a 10-cm GSD. Simulated output image (right) includes sensor and orbit-induced effects.

Several scene databases for various geographic regions are utilized in the simulation software. Relatively low resolution (30 meter GSD or above) databases in raster format are available for sensors with low resolutions. High-resolution databases are available in vector format for the simulation of high-resolution sensors. The simulation function supports the simulation of high and low spatial resolution panchromatic, multispectral, and hyperspectral images in the 0.4-2.5um spectral region.

Sensor simulations are based on Optical Transfer Functions (OTF's), which model sensor spatial response. The OTF calculations, which include both MTF's and phase transfer functions, take into account the following effects: optical diffraction, optical aberrations, detector size, linear motion, random and sinusoidal jitter, low-pass filter electronics, atmospheric turbulence, and aerodynamic boundary layer. MTF parameters are retrieved from the Knowledge Base based on the sensor and platform that have been selected by the user. The user has the option to modify these parameters dynamically to review their effects on the MTF curves. Figure 8 represents a plot of the various MTF curves. The system OTF is used to derive the point spread function (PSF) using an inverse Fourier transform. The input scene is then directly convolved with the sensor PSF. The calculations are performed in a discrete fashion with spatial sampling of the input scene significantly higher (7 to 15 times) than the sampling of the output image (oversampling). The OTF calculations and the convolution are performed separately for each spectral band of the sensor, and the output images are combined into an image cube when processing is complete. The effects of noise can be applied to the resulting image cube. Two types of noise can be modeled: detector/electronics noise, which is independent of scene radiance, and photon (quantum) noise, which is proportional to the square root of scene radiance. The sensor simulation functions were implemented using custom software developed in MatLab that was later converted to Java for incorporation within the VPL framework.

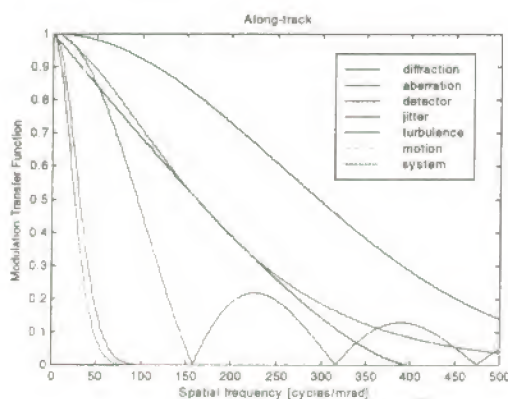


Figure 8. Along-track Modulation Transfer Function of a Simulated Sensor

The VPL currently allows users to save their simulated data as either band sequential or band interleaved by line format image files. An image viewer has also been developed for displaying the

input scene along with the simulated imagery to allow the user to view the effects of the PSF convolution and noise. Figure 9 shows the image viewer with the input scene on the left and the simulated image on the right.

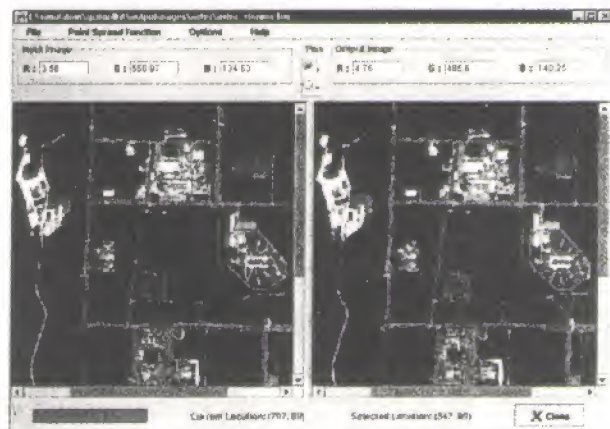


Figure 9. Simulated ASTER Sensor Image of SSC. Left image displays synthetic scene of SSC and right image displays scene after application of sensor PSF and noise.

The Simulation team is currently enhancing the existing optical sensor simulation capability and developing a thermal simulation function. Once these tasks are complete, the team will begin to investigate simulations for active sensors (SAR and LIDAR). Additional enhancements will include developing a 3-dimensional and 4-dimensional data visualization capability. Users will be able to view actual and simulated remote sensing data, map 2-dimensional images on 3-dimensional surfaces, and "fly" through images and 3-dimensional scenes.

Design and Analysis

The design and analysis functions will allow users to perform mission definition, compatibility analysis and integration, engineering trades and optimization, and error analysis. Tools used to perform these functions, including system design and mission modeling, will be accessible through the VPL. With these capabilities, users will be able to conduct design iterations and "What If..." analyses.

The Mission Definition function will provide a mechanism for defining components of a remote sensing mission. Users will be able to specify mission parameters, system components, and orbital characteristics. The Knowledge Base will provide users with access to system design information.

including characteristics, capabilities, and availability of remote sensing system components. A preliminary mission definition GUI has been developed, using Java, that allows users to identify their remote sensing mission components and orbital parameters. The mission component selection screen is displayed in Figure 10.

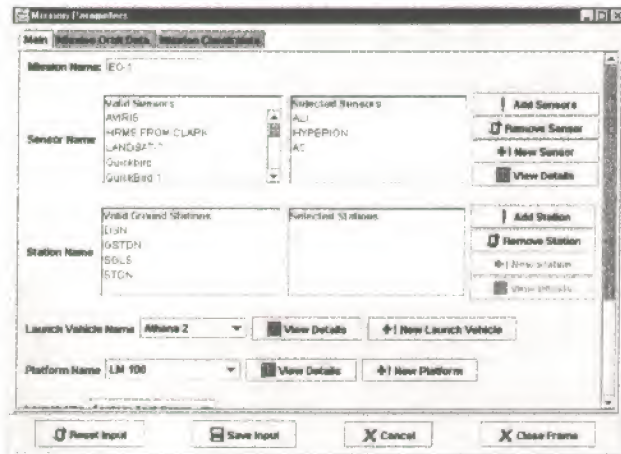


Figure 10. Mission Definition Screen for EO-1 Mission. The GUI allows users to define/select payloads and input other relevant information.

During the mission definition process, the user will be able to perform compatibility assessments related to remote sensing system infrastructure. System compatibility considerations offer a large range of often non-intuitive interface requirements. The VPL will provide the capability to assess and rank the compatibility of a given set of interface requirements in reference to pair-wise compared systems, such as sensor/platform and platform/launch vehicle. The user will have the ability to enable/disable assessment criteria to customize the mission assessment. Weighting factors can also be assigned to the criteria to prioritize critical areas for the mission. During an assessment, the system will provide a detailed report of the compatibilities/incompatibilities identified between the components. Users may choose to use the automated compatibility feature to locate compatible components within the Knowledge Base.

A high-level compatibility assessment capability has been developed for sensor-to-platform and platform-to-launch vehicle assessments. The compatibility analysis can be customized by enabling/disabling assessment criteria. Users can select a sensor and use the "find compatible" function to identify compatible platforms. The system also supports platforms with multiple payload attachment locations. Figure 11 represents a sample compatibility assessment screen.

Attribute	Required	Attribute	Supplied	Included	Compatible
Max Power	5.5	Max Power A.1	10	Yes	Yes
Keep Alive Power	0	Max Thermal	10	Yes	Yes
Height	0.74	Max Payload Weight	10	Yes	Yes
Width	1.54	Max Payload Weight	10	Yes	Yes
Length	0.51	Max Thermal	10	Yes	Yes
Total System Weight	230	Max Thermal	10	Yes	Yes
Design Life	0	Max Payload Weight	10	Yes	Yes
Min Sensor Altitude	1	Max Thermal	10	Yes	Yes
Max Sensor Altitude	500	Max Payload Weight	10	Yes	Yes

Figure 11. Sample Compatibility Assessment Screen for EarthWatch Multispectral Instrument and International Space Station Japanese Module (JEM) Attach Point

To aid in designing and analyzing remote sensing systems, the VPL will provide users with the capability to model a mission. Modeling will facilitate the understanding of system capabilities. The tools will allow users to perform coverage and link analysis based on sensor and orbital characteristics. Multiple analyses can be run over a short period of time to identify an optimal orbit design.

Current VPL modeling capabilities are based on two COTS packages: Satellite Tool Kit (STK) from Analytical Graphics, Inc., and Multidimensional User-Oriented Synthetic Environment (MuSE) from MUSE Technologies, Inc. STK is used to model existing and planned remote sensing missions and to perform coverage analysis. See Figure 12 for a sample STK display. Currently STK models (scenarios) are defined for Landsat-7, NASA's Terra, the Department of Energy's Multispectral Thermal Imager (MTI), Space Imaging Inc.'s Ikonos II, EarthWatch Inc.'s Quickbird, and the International Space Station (ISS). The scenarios are used for orbit modeling and sensor coverage analysis. Types of coverage analysis include simple, percent coverage, number of coverages, and amount of coverage over a period of time. STK has been integrated into the VPL GUI using the standard IPC protocol.



Figure 12. Sample Satellite Tool Kit Display Showing the Terra Spacecraft and its Instruments

The MuSE software package is being used to visualize a remote sensing instrument perspective from the ISS. SSC has obtained a MuSE application developed by NASA's LaRC that allows for the manual selection of payload attach points and provides a representative display of a defined instrument's field of view. The VPL team is currently working on modifications to this application to add flexibility to the user interface. In addition, the team is also developing a generic MuSE application for modeling a remote sensing system and its instruments.

Future enhancements for the design and analysis functions include providing the capability to conduct system trades and optimizations based on cost, performance, schedule, and design considerations. The user will be able to define parameter limits and system constraints to be used when performing the trades and optimizations. A detailed report will be generated of all subsystems affected during system trades analysis. The report will identify the options that were available at each step, their ranking (priority), and the option that was selected. The user will have the opportunity to compare and contrast the results of multiple system trades and to identify the best overall solution for the customer.

In the near term, the VPL team will continue collecting data on remote sensing missions and developing models to analyze these missions. Several design and analysis packages developed by LaRC are also being evaluated for incorporation into the VPL. Other near term tasks include automation of existing

capabilities, enhancements to the compatibility assessment function, and development of additional MuSE applications.

Project Management

The Project Management function will provide the capability to support business and project management decision-making associated with a remote sensing system. These tools will provide a business decision aid that will allow users to answer basic questions regarding their program ventures. Additionally, project management support capabilities will allow users to generate project plans, schedules, and cost estimates while accounting for risk, system trades, and typical pitfalls, such as lead times and resource loading. The user will be able to generate hard copy reports or export the data for use in traditional project management tools.

The VPL team is currently developing a rough order of magnitude cost estimation tool. This tool will project a market price for image products based on the cost of the system components, development, life cycle maintenance, current interest rates, and user-specified profit margin. More advanced capability in the project management area will be developed in the future.

Requirements Definition

The VPL will allow users to define, track, and verify the requirements for their remote sensing system. Users will have the ability to refine and track requirements as they progress through system design. At any point during the process, users will be able to save their requirements as a text document for creating a system-level requirements specification.

To date, no work has been performed on the requirements definition function. The first task will be to identify and evaluate requirements management software packages. A COTS, GOTS, or custom-developed package will then be integrated into the system.

Help

The system will provide hard-copy documentation, on-line help, and technical support for VPL users. Manuals describing system usage, operation, and maintenance procedures will be available. The VPL GUI will provide access to on-line user support in the form of context-sensitive help and on-line tutorials. For COTS and GOTS tools, help will be based on information provided by the tool supplier. The help

system will also provide a mechanism for users to report and track system problems, issues, concerns, and desires. The VPL system administrator will have the capability to review, log, and respond to these reports. Technical support personnel will be available for on-site users who require assistance during system operation.

Current VPL user documentation is limited to presentation materials and descriptions of individual functions. These materials will be incorporated into a User's Manual that will be accessible from within the VPL and as a hard copy document.

IV. SUMMARY

The VPL will allow users to evaluate simulated image products early in their remote sensing system design process. Thus, users can perform more effective design iterations and "What If..." analyses. Tools to support these studies, including engineering design, spacecraft modeling, and data simulation tools, are all accessible through the VPL. The Knowledge Base supports these functions by providing access to information about industry-wide components and systems. With the help of the VPL, the user has the capability to design, optimize, and simulate the performance of an entire remote sensing system within a virtual environment.

The VPL is currently accessible locally, on site at Stennis Space Center. Limited functionality can be accessed remotely (from off site) using terminal server client software for Windows NT. On-site users work hand-in-hand with VPL team members and simulation experts to address specific questions related to the customer's mission. The VPL will provide multiple levels of access control to restrict user access to non-public, proprietary, and sensitive information.

Customers interested in using the VPL are required to develop a formal agreement with NASA's Commercial Remote Sensing Program at Stennis Space Center. Agreements should focus on collaborative efforts that are beneficial to both the U.S. commercial remote sensing industry and NASA's Earth Science Enterprise.

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